



THE POWER
BEHIND THEIR WINGS



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HEAVY BOMBERS

HALIFAX · LANCASTER · STIRLING

MEDIUM BOMBERS

*WELLINGTON · ALBEMARLE
BUCKINGHAM*

LIGHT BOMBER

BLENHEIM

FIGHTER

NIGHT FIGHTER

TEMPEST II · BEAUFIGHTER

COASTAL COMMAND

*BEAUFORT · BEAUFIGHTER
SUNDERLAND · WARWICK BRIGAND*

FLEET AIR ARM

*ALBACORE · SWORDFISH
SKUA · FIREBRAND · ROC*

TRANSPORT

*BRISTOL FREIGHTER
BRISTOL WAYFARER
HANDLEY PAGE HERMES
HANDLEY PAGE HASTINGS
SHORT SHETLAND
VICKERS VIKING · AIRSPEED AMBASSADOR*

TRAINER

BUCKMASTER

O.P.D. 39/587



" . . . dressed in the blue and gold of the Hussars, a rolled map under his arm, he followed with the keenest attention the simple evolutions of the 'Boxkite'."

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*An account of the part played
by the Bristol Aeroplane Company
in the development of the
air-cooled radial aero-engine
in Great Britain*

FOREWORD

ON SOME RISING GROUND, dominating the wide sweep of Salisbury Plain, a group of British Staff Officers stood in animated conversation. From time to time certain distinguished figures—among them Lord Roberts, General Sir John French and Lord Kitchener—could be seen raising binoculars and scanning the horizon intently. Spread out in a vast panorama below them were units of the British Army engaged in their annual manœuvres.

It is safe to say that not one mechanically propelled vehicle was to be seen among the deploying troops. For this was September 21st, 1910—a year when encircling movements were entrusted to hard-riding cavalry regiments, and gun batteries were extricated from untenable positions behind smoking artillery teams.

But it was not for the unfolding of some such familiar tactical manœuvre that the little group on the hill waited so expectantly. Indeed, it was not with events on the ground that they were concerned at all. Their glasses were trained on the sky, far above the dust clouds raised by the galloping cavalry.

This year the Army Council, with a surprising departure from the traditional conservatism of the military mind, had invited well-known aviators to take part in the Army manœuvres. They were to prove, if possible, the suitability of their machines for dispatch carrying, reconnaissance and observation duties, and the Army Council, with a cautious eye on the public purse, had decreed that they should prove it, or not, at their own expense.

Here, then, was the reason for an excitement that can rarely have disturbed the serene atmosphere of the British High Command during a peace-time military exercise. For this was the day when it was known that Captain Dickson was due to give a demonstration of the new art of flying, and in particular to show that his machine could be adapted for strictly military purposes.

Taking the precaution of packing thick wads of newspapers underneath his overalls and jersey as a protection against a keen September

wind, Captain Dickson took off successfully, if a little hesitantly, in his Bristol "Boxkite". Perched out in an exposed position on the forward edge of the lower wing, he coaxed his primitive machine into describing a few turns and banks above the heads of an admiring and probably apprehensive audience, then set off purposefully across country on his military errand.

For this flight the "Boxkite" had been raised, in the eyes of its Bristol constructors, to the dignity of a "military type" by the simple addition of detachable wing extensions which gave it an increased lift of some 140 lb. The complete machine, with a framework of ash and spruce and fitted with a 50-h.p. rotary engine, weighed half a ton. In accordance with the usual procedure at that time, its cotton-covered wings were pasted with potato starch before the flight. With a maximum speed of 37 m.p.h., it had an effective flying range of 50 miles.

Was the full significance of this, the first official military flight in England, grasped by the military strategists of that time? It is hardly likely. As yet they could have had no hint of the transformation in warfare to be brought about by the internal combustion engine on land. It needed an exceptional leap of the imagination to anticipate its conquest of the air.

Yet supporters of the aeroplane for military purposes were not wanting even in 1910. The flight certainly aroused a storm of criticism and controversy in the Press; some staunch champions of the aeroplane had to fall back on the argument that it would at least enable observations to be taken immune from the risk of rifle fire.

Whatever the professional strategists thought, it is safe to assume that one watcher on that memorable September day was deeply impressed. A sturdy figure in the middle thirties, mounted on a well-groomed chestnut and dressed in the blue and gold of the Hussars, a rolled map under his arm, he followed with the keenest attention the simple evolutions of the "Boxkite". We do not know what thoughts or visions flashed across that lively, receptive mind. We do know that from September 1910 a certain Mr. Winston Churchill, late of the Hussars and at that time one of His Majesty's Cabinet Ministers, became a most enthusiastic advocate of the military aeroplane.

One year later, Mr. Haldane, the British Minister for War, ordered

four Bristol "Boxkites"—the first contract for military machines ever placed with a manufacturer by the British Government.

From that day the Bristol Aeroplane Company, the largest single organization in the British Empire concerned with the manufacture of airframes and aero-engines, has always been closely connected with the development of the aeroplane for military purposes. The company designed and built the most famous fighter of the last war. The "Bristol" Fighter, powered with a Rolls-Royce "Falcon" engine, saw more service on all fronts than any other aeroplane of the day. It was this fighter that finally proved superior to the excellent German Fokker, and that certainly turned the scales in favour of the Allies in the air during the crucial days of 1917 and 1918.

In this war, in addition to the building of airframes, Bristol have produced, in their sleeve-valve series, some of the outstanding air-cooled radial engines in the world, of which the most famous as yet is the "Hercules".

The Bristol "Hercules" has been the power behind the wings of marks of all the heavy British aircraft of the war—the "Stirling", "Halifax" and "Lancaster" heavy bombers. It has powered the incomparable Bristol "Beaufighter" which won the night battle of Britain as surely as "Hurricanes" and "Spitfires" won the day battle. It is the "Hercules" that powers the Vickers "Wellington", for so long the mainstay of Bomber Command, and the "Albemarle", which played a great part in the landings in Sicily and on D-Day.

The story of the development of the "Hercules" is almost the story of the development of the air-cooled radial engine itself—an aero-engine type that powers practically every first-line commercial aircraft in peace time and which has played so great a part in the crushing of Germany's armament industry from the air. For Bristol were the pioneers of the radial engine, and it would be true to say that their research work in the early days has influenced its development and construction in every country with an aircraft industry. The story is of interest, too, in revealing something of the reserves of skill and determination that Britain could call upon when she had to wage the type of mechanized warfare that depends as much upon the ability of designers at the drawing-board and technicians in the testing house as on the courage of the fighting men who handle complicated modern weapons on the field of battle or in the skies above it.

“Ordinary Engineering made more difficult”

A MOTORIST TO-DAY, who takes for granted the reliability and performance of the efficient, streamlined power unit of his car, probably thinks of an aero-engine as a bigger and more complicated development of a modern car engine. He would be right—and he would be wrong. Right, because it was the rapid improvement of the internal combustion engine for the motor-car that pointed the way for its development as the prime mover of a practical flying machine. Wrong, because the normal course of development that has brought the motor-car engine to its present pitch of efficiency would not have been sufficient to produce an internal combustion engine suitable for a modern aircraft.

An altogether new line of development, a more intense research into the qualities of metals, had to be pursued in the aero-engine field. In particular the aero engineer, faced with the problem of designing a power unit capable of lifting off the ground its own weight and that of the aircraft in which it is installed, has been concerned to a far greater extent than the automobile engineer with the power-to-weight ratio of his engine. Both have struggled to increase efficiency, to achieve greater smoothness and reliability, and a longer life between overhauls. But, in addition, the aero engineer has had to measure the effectiveness of his design strictly in terms of horsepower per pound weight of the complete engine. Thus the latest type of Bristol radial aero-engine produces approximately 1 brake-horse-power for each pound of engine weight. An efficient modern car engine would produce about 1 b.h.p. for every $6\frac{1}{2}$ pounds of engine weight. This is not to say that the automobile engine is not a thoroughly efficient power unit for its special purpose. But it is a measure of the new set of problems that have had to be solved by the aero engineer working

under limitations that do not apply to the designing of an automobile engine.

The special problems which face the engineer in designing the structure and power plant of an aircraft have been recognized in a well-chosen phrase by Dr. R. V. Southwell in the James Forrest Lecture to the Institution of Civil Engineers. "Aeronautical engineering", he said, "is ordinary engineering made more difficult."

The development of the aero-engine over the last quarter of a century can be traced in two simple curves. A descending curve which shows a reduction in weight per brake-horse-power from 4 lb. to approximately 1 lb. ; an ascending curve which shows the production of brake-horse-power per square inch of piston area rising from 1.5 b.h.p. to approximately 6 b.h.p. Thus, while the weight of an engine for a given horse-power has been cut to one-fourth, the power produced from an engine of given size has been increased fourfold.

How has the aero engineer achieved so great an increase in power with an equally remarkable reduction in weight? The answer to this question must range over the whole field of development in the aero-engine industry—design, development work, metallurgical research, production techniques; and it must glance at the achievement of a great body of technicians over many years.

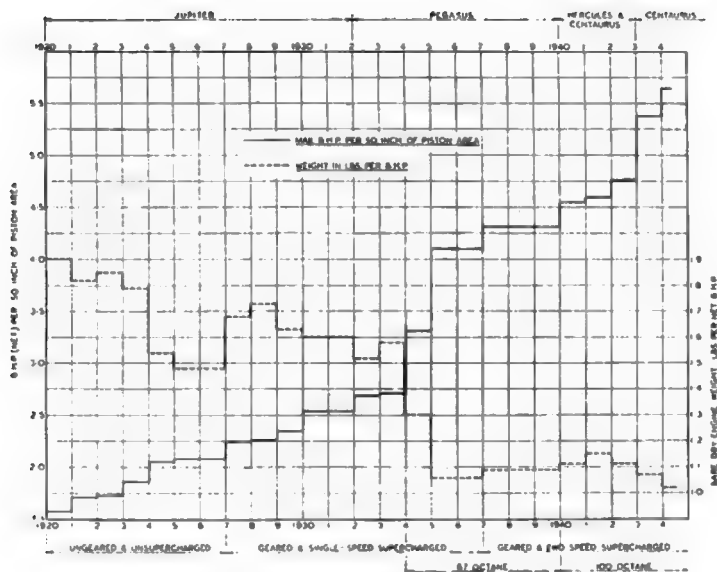
Broadly, the improvement in performance, and in the specific power-to-weight ratio of the aero-engine, can be attributed to four main factors. First, the discovery of aluminium alloys; secondly, continual detailed improvement in design throughout every component of the engine; thirdly, the development of the supercharger; fourthly, the introduction of tetra-ethyl-lead fuels and 87- and 100-octane fuels with marked anti-knock properties.

First, and most important, has been the discovery of aluminium alloys capable of withstanding the great stresses imposed by a high-efficiency internal combustion engine, yet so light that their use in place of steel and cast-iron completely changes the power-to-weight ratio. Certain of these high-duty alloys, as they are called, have a tensile strength of 40 tons per square

inch—as great as that of medium carbon steel. Yet these alloys weigh only one-third as much as a steel of equal strength. Ninety years ago aluminium was a precious metal costing over 2,000 shillings a pound. To-day an aluminium ingot costs about a shilling a pound. Aluminium and its alloys have made the modern aircraft and aero-engine a practical possibility. Over three-quarters of the weight of the frame of a modern bomber, and about half the weight of its aero-engines, consist of aluminium alloys.

Throughout the whole history of engineering the inventive genius of the designer has been limited by the materials at his command. One of the earliest and most dramatic instances is to be seen in the designing of James Watt's first practical steam-engine. The cylinder for this, to ensure accuracy of bore, had to be made of block tin—a material which speedily collapsed under the stresses imposed. At this stage a famous ironmaster came to the great inventor's assistance. He had recently perfected a machine for boring the cast-iron barrels of cannon. His machining process gave an accurate bore over the whole length of the barrel and, applied to a cylinder for Watt's engine, resulted in the production of a perfect bore in a material of the requisite strength. With this cast-iron cylinder Watt could report that the first steam-engine using a condenser was a success. It is interesting to note that it was not sufficient that the material—cast-iron—was at hand. A machine tool had to be constructed before that material could be shaped for the inventor's special purpose. So the work of the designing engineer has historically been modified by, and to a great extent dependent upon, the work of the metallurgist, and the practical production engineer in the workshop. This has been particularly true of the aero-engine industry, where highly stressed parts machined to very fine tolerances have had to be made under flow-production conditions in the factory. The practical limitations imposed by quantity production exert a profound influence on the designer's scheme.

The second important influence in aero-engine development has been the building up of many detail improvements in



DEVELOPMENT OF BRISTOL AIR-COOLED RADIAL AERO-ENGINES

These two simple curves, based on the performance of "Bristol" engines, give a clear picture of the development of the air-cooled aero-engine over the last quarter of a century. Over this period it will be seen that while the weight of the engine for a given horse-power has been cut to one-fourth, the power produced from an engine of given size has been increased four-fold. Four main factors have influenced this remarkable increase in efficiency. Intensive metallurgical research, and the development of new alloys, have brought about a progressive decrease in weight; detailed improvement in design has increased specific power output; the introduction of the supercharger in 1927 resulted in still greater power being developed—particularly at high altitudes; finally the introduction of 87-octane fuel in 1934, and 100-octane fuel in 1940, resulted in yet another marked increase in power output without any radical change in design. Improved performance has presented the designer and metallurgists with many problems to solve. In particular it has meant the designing of components capable of withstanding greatly increased stress. Whereas the greatest load on a bearing of the "Jupiter" engine at maximum power and speed in 1920 was 5 tons, the greatest load on a bearing of the "Hercules" engine in 1944 had risen to 18 tons.

design until an engine with a totally new order of performance gradually emerges.

Thirdly, the application of the supercharger, so that a greatly increased charge could be forced into the combustion head, had an immediate effect in raising engine performance—particularly at high altitudes.

Finally, the introduction of tetra-ethyl-lead, 87-octane, and now 100-octane fuels, with special anti-knock properties, greatly increased the power output from a given piston area. Between 1918 and 1930 the specific horse-power of the aero-engine was increased by about 40 per cent., and it is probable that half of the increase was due to improvements in the anti-knock properties of fuel.

But it should be borne in mind that in the aero industry perhaps the most important limiting factor, once the original design has been conceived, has always been the development of materials strong enough to withstand the stresses imposed, yet light enough to give a particularly favourable power-to-weight ratio in the completed engine.

Thus it can be seen that the development of the aero-engine has been due less to the intuitive genius of individual designers than to the combined work of highly qualified research teams each of which has had its own special field of inquiry and its own special problems to solve.

There can be no better illustration of the value and effectiveness of teamwork in the aero industry than the progressive development from the Bristol "Jupiter" engine, first designed a quarter of a century ago, to the Bristol "Hercules" which powers so many of Britain's first-line aircraft.

Over this time the design and development staff of the Bristol aero-engine section has grown from the 35 originally employed under the chief engineer in 1920 to approximately 1,000 to-day—630 highly qualified technicians, assisted in the tabulation and recording of their work by 372 in clerical grades. That so considerable a staff should be concerned solely with design, research and development work is itself a measure of the size of the organization necessary to keep abreast with day-to-day developments in the aero-engine field.

How far-reaching is the development work that must be undertaken—what breadth of vision and foresight are required—are well instanced by one piece of work to which this growing team set their hands. The poppet-valve mechanism, familiar to motorists, is not a perfect method of charging and exhausting the combustion head in a high-powered aero-engine. So the Bristol Company determined, as early as 1927, to put in hand a programme of development work which included a thorough testing of all alternative valve systems, and after the choice of the single sleeve as the type for full development, they persevered for ten years, in the face of innumerable difficulties and disappointments, before its adoption in the "Perseus"—the first aero-engine to go into large-scale production fitted with sleeve valves.

It is significant that in 1927, when this long-range research programme was put in hand, the Bristol "Jupiter" radial engine, fitted with the conventional poppet valve, was proving one of the most successful aero-engine types ever produced and was being made under licence in 14 different countries. Bristol's determination, in spite of this success, to go ahead with research work on extensive modifications is characteristic of the critical approach to design problems, the continual drive for improved performance, and an intuitive feeling for engineering developments that are the prerequisites of progress in the aero-engine industry. The perfection of the sleeve valve was the work of an enthusiastic team; the inspiration and co-ordination of the work came from a lively imagination with a sure grasp of the essentials of an engineering problem.

It is certain that the beautiful simplicity of the single-sleeve mechanism had appealed to the engineering purist ever since its invention in 1909. However, it required courage and foresight on the part of the Bristol Company and its chief designer to embark on the extensive research programme needed in view of the great practical difficulties then existing in the way of its application to a high-duty, high-speed engine. And it is pleasant to record here that in this decision the Bristol Company received considerable technical and financial support from the British Air Ministry. It may come as a

refreshing surprise to the critical layman to learn that Government departments are not always distinguished by perverseness and lack of imagination, even when making incursions into highly technical fields.

In the Bristol Company, then, the development of the sleeve valve was preceded by, and over a long period ran parallel with, the continued improvement of the air-cooled radial type using the conventional poppet valve. It will be convenient, therefore, to trace the development of both types separately, bearing in mind that all the poppet- and sleeve-valve Bristol engines used in first-line British aircraft have been of the air-cooled radial design.

The Evolution of the Air-cooled Radial Engine

IN THE EARLY DAYS of the internal combustion engine its development was in the hands of the motor-car manufacturers and, as was natural enough, their whole energies for many years were directed to improving types suitable for the motor-car. Even after the Wright brothers had demonstrated, in their historic flight in 1903, that the internal combustion engine was destined to become the prime mover of the flying machine, it was some years before the motor manufacturers in Great Britain and America felt any inclination to turn their attention to the special problems raised by the aircraft power plant.

In France, however, the future of the flying machine seems to have excited the lively Gallic imagination from the very first. It was not surprising, therefore, that we found French designers concentrating on the development of an internal combustion engine specially suited for aircraft. The conventional four-cylinder and six-cylinder water-cooled motor-car engines of the time were comparatively heavy, slow running and rough. They set up vibrations in the airscrew and the flimsy, wire-braced wooden airframes. This vibration constituted a serious problem for the airframe designer.

It was found that a multi-cylinder, air-cooled rotary engine, with considerable flywheel effect, was simpler, lighter and smoother running than the existing in-line, water-cooled motor. And, of course, the flow of air around the engine when mounted in a flying machine solved cooling problems that called for elaborate water-jackets in the case of the motor-car engine.

The air-cooled rotary engine, therefore, became very popular with the adventurous pilots, both French and British, in whose hands the new sport of flying rested.

By 1910, however, military authorities in many countries

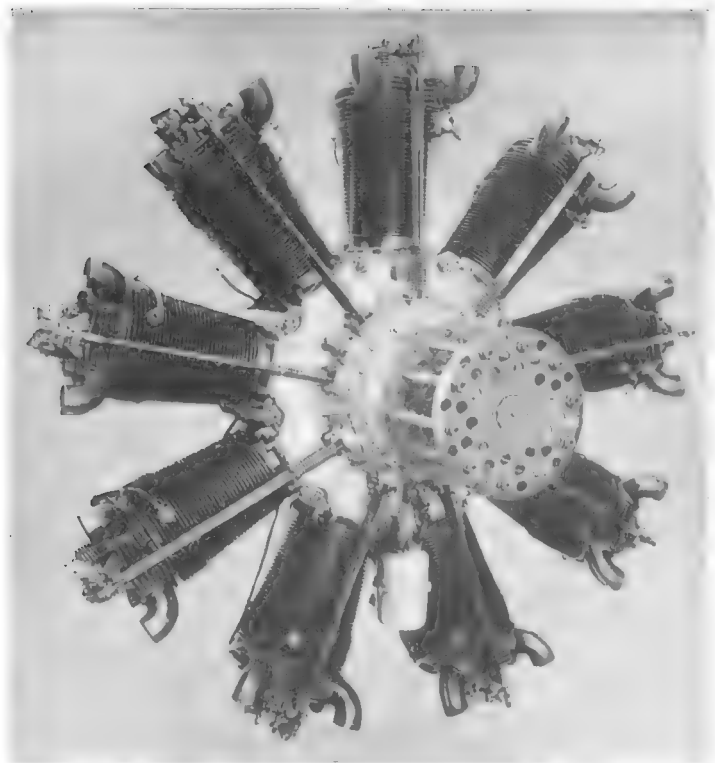
had begun to cast speculative eyes on the flying machine. As we have seen, it was in this year that the first military trials of the new invention were held in Great Britain. The flying machine did not remain for long the preserve of the enthusiastic amateur. By 1914, the British, French and German Governments had held competitions to encourage the development of the most suitable type of engine for military purposes. Some motor-car manufacturers, sensing Government orders in the air, now began to pay serious attention to the aero-engine; others at the outbreak of the last war launched out into large-scale designing and development work in a patriotic desire to supply their Government with the new air weapon. In fact, it can be said that it was during the last war that the making of aero-engines in Great Britain became one of the most important national precision industries.

As was to be expected, motor-car manufacturers tended to develop the engine type with which they were most familiar and on which a great deal of research work had already been completed—the in-line or V-section water-cooled motor. On the other hand, firms who had specialized from the first in building aero-engines concentrated on the improvement of the air-cooled radial—the type that had grown out of the rotary engine.

Thus, in the earliest days of the aero-engine industry there were two clearly marked, successful and parallel lines of development open to the engineer—one centring around the air-cooled radial engine, the other around the in-line or V-section liquid-cooled engine.

The two chief aerodynamic problems in the designing of the heavier-than-air machine have always been the reduction of drag and the improvement of stability and control.

Broadly speaking, drag is the resistance of the air to a body moving through it—and it varies as the square of the speed of the moving body. Designers wishing to build a fast military fighter, therefore, for long favoured the V-section liquid-cooled engine which had a much smaller cross-sectional area than the air-cooled radial, with its typical sunflower shape. On the other hand, for bombers and civil transport machines,



The "Jupiter" air-cooled radial engine the engine from which the "Hercules" can be said to have been evolved. The "Jupiter"—perhaps the most famous engine series ever developed—has been built, under licence, in every country with an aero-engine industry.

where speed was not so essential, but simplicity, reliability and ease of overhaul were important factors, designers have in the past gravitated towards the air-cooled radial engine. Both engine types have fulfilled important functions in the past—both continue to do so now. It is worth noting, however, that before the war the air-cooled radial engine was fitted to the great majority of large civil transport aircraft in use throughout

the world; and even in the military field it has been estimated that at the outbreak of the war 55 per cent. of all military motors in British first-line aircraft were of this type.

It would seem, therefore, evidence of a certain intuitive sensing of the needs of the aircraft industry that the Bristol Company should decide, as far back as 1920, to concentrate on the development of the air-cooled radial engine. Experience of air fighting in the last war appeared to favour the liquid-cooled type, for the great majority of aircraft on both sides had been powered by the V-section, or in-line liquid-cooled engine. However, with a foresight that has been amply justified by results in civil aviation, the Bristol Company pinned its faith to the air-cooled radial engine.

The first Bristol engine to go into serious production was the "Jupiter"—a nine-cylinder air-cooled radial engine fitted with the conventional poppet valve, but embodying many refinements of design compared with contemporary engines of similar type. This is the engine from which, over a period of nineteen years of research and experiment and of practical results under every conceivable flying condition, the famous 14-cylinder "Hercules" of this war can be said to have evolved.

The success of the "Jupiter" proved that the air-cooled radial engine was an ideal power plant for the civil air liner. It became, in its time, probably better known to aero engineers the world over than any other series ever built. To show how it influenced the design of air-cooled radial engines in all countries, it is only necessary to record some of the engineering refinements first appearing on the "Jupiter" which subsequently became the standard practice of all manufacturers building this basic type.

In 1923, the "Jupiter" was the first radial aero-engine in the world to employ a one-piece master connecting rod and coupled crankshaft construction; in 1928 it was the first aero-engine built with a forged duralumin crankcase—resulting in a saving of 80 lb. in weight and a reduction of its frontal area by 12 per cent.; in 1928 it was the first aero-engine to go into production with a gear-driven supercharger; in 1929 it was

the first aero-engine fitted with forged aluminium cylinder heads—Bristol, indeed, have led the world in substituting aluminium forgings for castings in aero-engine work; in 1930 it was the first production engine to be fitted with an automatic boost control—an ingenious device which prevents possible damage to a supercharged engine through incorrect handling of the pilot's throttle lever.

To aero engineers all over the world each of these refinements represented a definite step forward in aero-engine design; their introduction over a period of years meant that from 1920 to 1930, ten vital years in the development of the radial engine, British designers were leading the world in technique in the building of air-cooled radial engines.

By 1930 the "Jupiter" was being built, under licence, in fourteen different countries, including all the countries that were making the greatest contributions to aeronautical science during that time.

While the success of the "Jupiter" was essentially a matter of superior design, it could not have been achieved without the help of the production engineer. Designing and building an aero-engine are very much a matter of teamwork from the time the first drawings come from the drawing-board until the engine goes on to the assembly line. A good experimental engine on the test bench does not always mean a successful engine in series production. A scheme that delights the critical eye of the designer may present insuperable difficulties to the production engineer who must tool up a factory to produce intricate components in quantity. The good designer, therefore, is always striving for simplicity—for a reduction in the number and complexity of working parts. He must compromise between his desire to find the ideal solution of a design problem and his knowledge of the limitations set by materials and processes when his design goes out of the experimental shop and on to the production line.

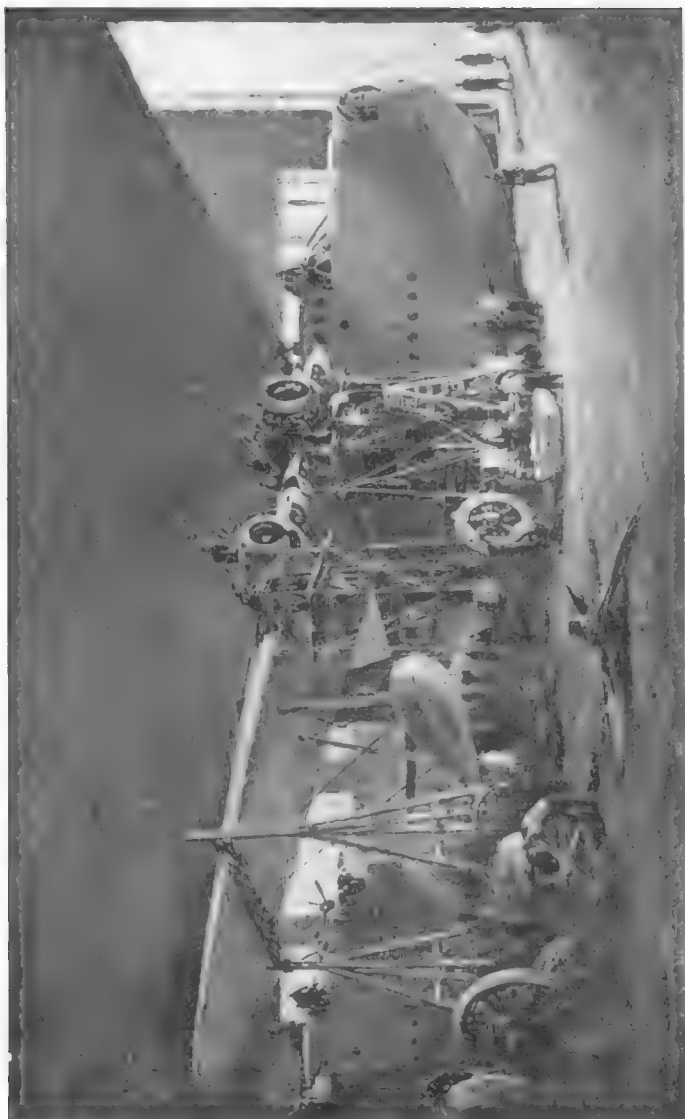
Here it is, perhaps, that the British designer is placed in a specially favoured position. For he can always rely on the sure craftsmanship and conscientious inspection at every stage of production that has become an inborn tradition with the

British engineer. The British designer can introduce refinements which present great difficulties to the production engineer, relying on his countryman's natural aptitude for engineering to triumph over those difficulties in the tool-room and at the bench.

This dependence of the designer on the production engineer can be illustrated by the way in which certain cooling problems have been solved by Bristol engineers. Everyone is familiar with the finning of a motor-cycle engine. The fins serve an important purpose—they greatly increase the surface area of the cylinder barrel and head that is exposed to the air. Thus, heat is conducted away more quickly. The same principle applies to the cylinder head of an air-cooled aero-engine. Obviously the more fins that can be cut in a given area, and the deeper they are cut, the greater the cooling effect. But the cutting of fins from the solid in making a forged aluminium cylinder head is a difficult machining process. Bristol production engineers solved the problem by developing special tools that enabled more closely pitched fins of greater depth to be cut into the solid metal. The increased cooling area obtained allowed the designer to take advantage of a stepping up in engine performance that would otherwise have resulted in overheating. Theoretically, the designer had no difficulty in deciding on the closeness and depth of finning in a given area needed to give efficient cooling. Practically, he was dependent on the production engineer devising a machining process that would allow the ideal scheme to be carried out on the production line.

The care with which quality control of materials has always been carried out at the Bristol works and the irreproachable workmanship that went into every "Jupiter" engine on the production line were proved time and again in special tests. Three of these, each one of a severity never before attempted in the aero industry, are worth recording.

In 1923, a production engine completed a 150-hour thrust test at 90 per cent. normal power, including non-stop runs of 30, 35 and 55 hours. Detailed examination after the test showed that the average wear in major components was



SERVICING A "SUNDERLAND"

Charles Cundall, A.R.A.

only .0005 inch. The complete engine was in excellent condition.

In 1926 it was decided, as a demonstration of the reliability of a Bristol-built high-duty aero-engine under working conditions, to embark on an exceptionally gruelling endurance test. It is probable that no other internal combustion engine, in the aero or automobile industries in any country, had ever been submitted, up to that time, to a test of such severity. A production engine was taken from stock, sealed up by the British Aeronautical Inspection Directorate, and installed in a "Bristol Bloodhound" fighter. Still under official supervision, the aircraft was then flown for a total of nearly 226 hours, covering over 25,000 miles, without breaking the seals or making any replacements. The flights were made in the winter of 1926, and included long periods at full throttle due to adverse weather conditions. When stripped for examination the condition of the engine was excellent; the only replacements required to put it in perfect order for further flying were one exhaust valve and one exhaust valve spring. Later in the year the same engine, with these two replacements, completed a trans-continental flight of some 6,000 miles from London to Cairo and back in approximately 60 flying hours.

The third test demonstrates that a modern aero-engine is, in every sense of the word, a piece of precision engineering.

Six "Jupiter" engines were taken from stock and passed through routine tests. Then all six were stripped down and each set of components handed over to the Aeronautical Inspection Directorate inspectors. No fewer than 1,500 parts were interchanged before the six engines were reassembled and no particulars of these changes were disclosed to the Bristol Company. No difficulty or need for special adjustment was encountered in assembling any one of the engines, and after each had been tested once more and stripped down, only one small part of all those interchanged was rejected by the inspectors. The British Air Ministry then accepted all six engines, with interchanged parts, exactly as they came from the test.

Parallel with the production of the "Jupiter" engine, the

Bristol "Mercury" series was introduced in 1926—an engine of the same basic type but smaller in cubic capacity and developed primarily for high-speed fighting aircraft. The "Mercury" engines were subsequently chosen to power a remarkable passenger aircraft produced by Bristol airframe designers in 1936. Constructed to demonstrate the ability of a British-designed aircraft to hold its own, both for speed and sound design, against world competition, it proved faster by some 50 m.h.p. than contemporary single-seat fighters.

It was from this aircraft that the "Blenheim" light bomber was developed—the first all-metal stressed-skin monoplane, and the first aircraft to carry its bomb load inside the main structure of the fuselage. The "Blenheim" was in many respects a revolutionary machine. Its Bristol designers, both of engines and airframe, can fairly claim to have proved that a British-built aircraft could lead the world in design and performance for high-speed military types.

The "Jupiter" was followed by another equally famous series of Bristol poppet-valve engines—the "Pegasus", first introduced in 1932. This engine, of exactly the same type and size as the "Jupiter", continued in the same line of development. By 1939, although of the same cubic capacity, it was producing roughly three times the horse-power of the first "Jupiter" of 1920. Thus, in the space of nineteen years through intensive research covering all fields of engineering in the aero industry, the power output from a radial engine of given size had been trebled. In the same period the weight of the engine had been decreased by 43 per cent., in spite of the addition of gearing, supercharger, and an extensive range of modern accessories. Maximum crankshaft speeds had been increased by 80 per cent., and fuel consumption reduced by 25 per cent. In the light of these achievements it can be claimed that Bristol engineers have played as great a part as those of any other single organization in the evolution of the air-cooled radial engine. The success of Bristol designs undoubtedly influenced aircraft designers to adopt this engine type in practically every large civil transport plane in use all over the world between the two wars.

Imperial Airways, for instance, first adopted Bristol "Jupiter" engines in six "Heracles" airliners in 1926. In 1936, Bristol "Pegasus" engines were chosen for the fleet of thirty Short Empire flying-boats put into service by Imperial Airways. It is interesting to record that in 1943 twelve of these original machines, including the first three launched, were still flying. In the three years 1941, 1942 and 1943, the engines in these twelve machines ran a total of 1,272,065 hours with periods of 600 hours flying between overhauls—a remarkable demonstration of reliability.

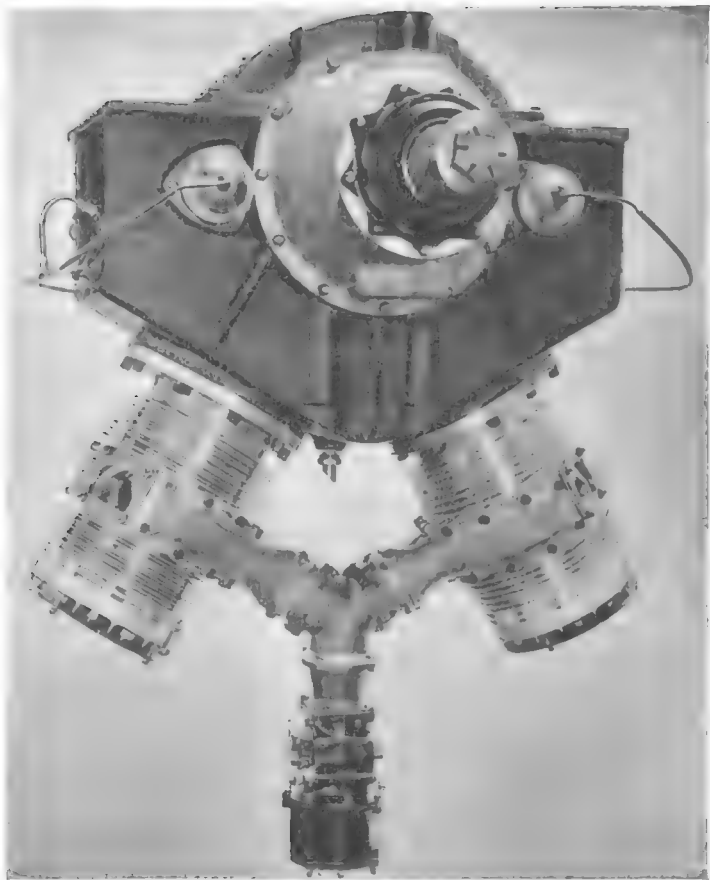
Bristol engines have been holders of many world records. Here are some of them. Five times holder of world height record in eight years—41,790 ft. in 1929, 43,976 ft. in 1932, 47,360 ft. in 1934, 49,967 ft. in 1936, 53,937 ft. in 1937; first air-cooled engine to pass 100-hour full throttle type test; first air-cooled engine to pass 300-hour full throttle test; holders of the world record long-distance non-stop flight of 7,162 miles in 1938 when fitted to "Wellesley" bombers of the R.A.F. In 1937 a Short Empire flying-boat, fitted with four "Pegasus" engines, made the first commercial transatlantic flight and the fastest crossings made, up to that time, in both directions.

All these are achievements of Bristol poppet-valve engines. A record outstanding enough, one might think, to satisfy the most exacting staff of designers. But even while these records were being made, even as far back as 1927 research work had been started on an entirely new type of radial engine—work that culminated in the designing of the sleeve-valve "Hercules" in 1935.

A designer's vision— the development of the sleeve-valve aero-engine

IN THE EARLY DAYS of the internal combustion engine—something like forty years ago—designers were already searching for a positively controlled valve motion to replace the poppet valve. Yet to-day the poppet valve is still used in automobile and aero engines of the most advanced design and at the highest level of performance and reliability. Here is an interesting example of a principle touched on in the last chapter—the limitations imposed on the designer by materials and production processes available. Theoretically, the single-sleeve valve invented in 1909—now generally referred to as the Burt-McCollum type after its two patentees—has always shown definite advantages over the poppet valve. In practice, difficult problems were raised in the machining of the sleeve to the very fine tolerances and finish necessary for successful operation in a high-duty aero-engine. Designers preferred to continue with the improvement of the well-tried poppet valve rather than embark on the elaborate research programme necessary to solve the practical difficulties in making the sleeve valve. It should be pointed out that patent rights also acted as a hindrance to the early development of the Burt-McCollum principle. However, the chief difficulties, and they were formidable, lay in the production of a sleeve that would operate successfully under the severe conditions imposed by a high-speed, high-efficiency aero-engine.

It is a measure of these difficulties that Bristol engineers thought it necessary to spend four years' work on research units to test the sleeve-valve principle under every possible condition before a complete engine was constructed. In aero-engine practice the usual research unit is a single cylinder (it may, however, consist of two or more cylinders) mounted and



A typical research unit used for development work on the sleeve valve. No less than 30,000 hours' testing of the sleeve valve in research units was undertaken by Bristol engineers before its incorporation in a complete engine.

run in a test house. It is subjected to every possible modification affecting, for example, compression ratio, running speeds, cooling or ignition systems and so on. Not until the engineers are fully satisfied with the design and performance of the research unit is a complete engine constructed and in its turn subjected to careful testing on the bench.

In carrying the single-sleeve valve principle to the stage at which it was deemed safe to incorporate it in a complete engine, no fewer than 30,000 hours' testing of research units took place at Bristol over the first four years of the research programme. A further 14,000 hours' development, type testing and flight trials of the complete engine were then undertaken.

The first complete Bristol sleeve-valve engine built in quantity was named the "Perseus". It was of the same basic type as the "Jupiter"—an air-cooled, nine-cylinder radial—and as well as the sleeve-valve mechanism it embodied all the refinements of design developed in the "Jupiter", "Mercury" and "Pegasus" poppet-valve types.

The "Perseus" was submitted to its first standard 100-hour Air Ministry type test in 1932—five years after Bristol decided to lay down a full-scale research programme on the Burt-McCollum sleeve valve adapted to the air-cooled radial aero-engine. Results of the test were most satisfactory in every way; but Bristol engineers were far from satisfied. Indeed, the test was regarded as merely laying the foundation for an exhaustive programme of research on the bench and in the air, in order to make certain that no unforeseen factor should arise to throw doubt on the practicability of the sleeve-valve principle under service conditions. It was not until another five years had elapsed that the "Perseus", in 1937, became the first aero-engine in the world fitted with sleeve valves to go into quantity production.

Here it may be of interest to the more technically minded reader to consider briefly the sleeve-valve principle in comparison with the poppet valve. Every motorist is familiar with the poppet valve, and has a rough idea of how it is operated by a cam and a powerful return spring. The valve head sits down on to a valve "seating" and so closes the port through

which, in the case of the inlet valve, fuel enters the cylinder or, in the case of the exhaust valve, burnt gases are ejected from the cylinder. The mechanism needed for this closing and opening operation—the valves, springs, valve guides, camshaft, rocker arms and so on—is elaborate and, in a high-duty engine, needs a good deal of careful inspection and maintenance. The behaviour of the poppet valve at great speeds is extremely interesting. Observed under an oscilloscope—an instrument that makes it possible to watch a fast-moving valve in “slow motion”—it is seen that at high speeds the valve does not return to its seating and remain there. It actually bounces, sometimes two or three times, thus partially opening a port that should be firmly sealed for the development of full power from the engine. Moreover, the spring, as the speed of the engine increases, tends to store up energy of its own which, when expended, causes the spring to expand suddenly, with the consequent risk of fracture. There is no doubt that the valve spring remains one of the limiting factors in the development of the poppet-valve engine.

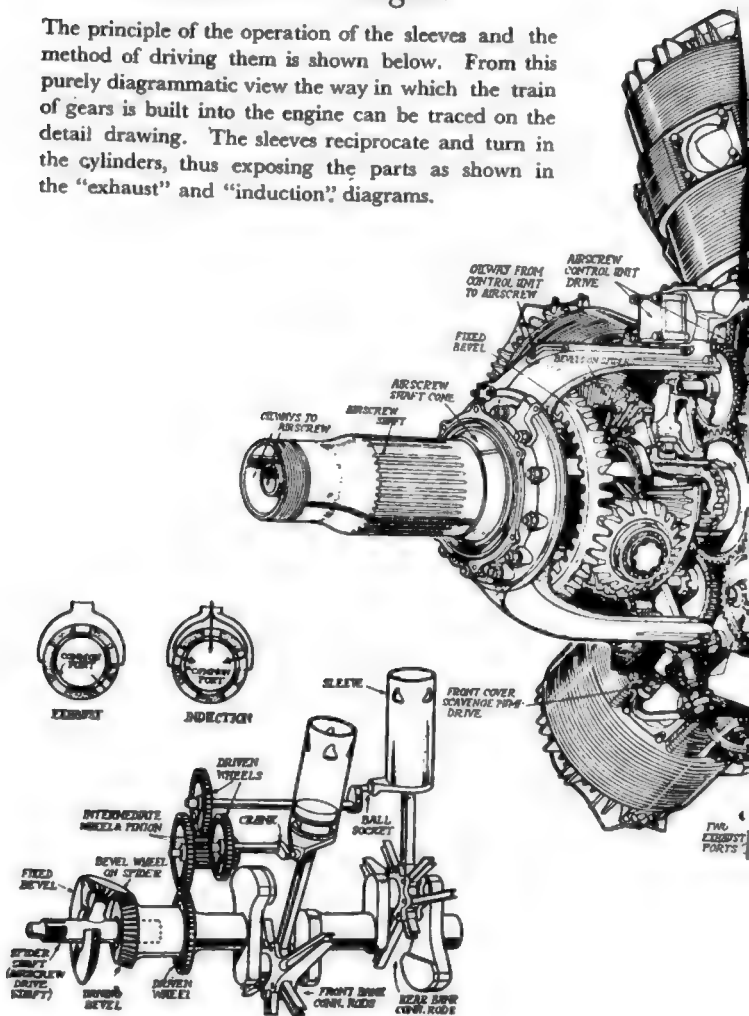
In spite of these disadvantages, brilliant research in Great Britain, and more particularly in America, has enabled designers to incorporate poppet-valve systems giving excellent results. The poppet valve has been used, as has been described here, with great success by Bristol designers up to this day. None the less, it is not a system that can give full satisfaction to the exacting engineer. Even in 1926 Bristol engineers felt that the poppet valve was bound, sooner or later, to set limitations in the full development of the piston engine. It seems likely that their conviction will be justified by the future development of the piston engine—at least in Great Britain. For it is probable that the sleeve valve, pioneered by Bristol engineers, will in time replace the poppet valve on high-efficiency piston engines of all types, both air- and liquid-cooled, built by British engineers.

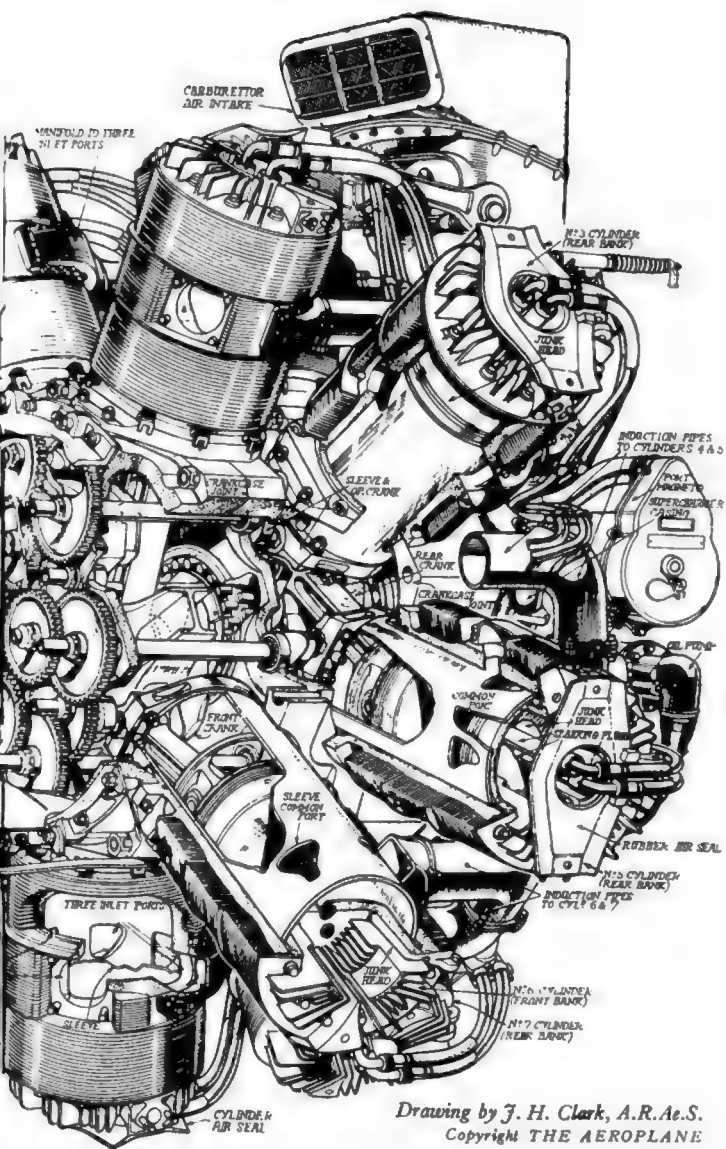
The single sleeve is a beautifully simple solution of the problem of opening and closing the inlet and exhaust ports of the piston engine. The sleeve, as its name implies, is a complete cylinder with apertures cut in the wall to correspond with

THE BRISTOL "HERCULES"

14-cylinder, Two-row Air-cooled Radial Aero-engine

The principle of the operation of the sleeves and the method of driving them is shown below. From this purely diagrammatic view the way in which the train of gears is built into the engine can be traced on the detail drawing. The sleeves reciprocate and turn in the cylinders, thus exposing the parts as shown in the "exhaust" and "induction" diagrams.





Drawing by J. H. Clark, A.R.Ae.S.
 Copyright THE AEROPLANE

similar ports cut out of the cylinder proper. It is fitted between the cylinder wall and the piston. Actuated by a crank driven from the main crankshaft through a train of gears, it alternately slides up and turns in one direction, then slides down and turns back in the opposite direction. This combined reciprocating and rotary motion closes and opens the inlet and exhaust ports in the correct sequence and time in the cycle of operations.

The outstanding advantage of the single sleeve is its simplicity and a great reduction of working parts compared with the poppet-valve mechanism. In particular, it eliminates the vulnerable valve spring. The sleeve, because it is positively operated through a train of gears, needs no adjusting; valve timing cannot vary once the engine is assembled.

An engineer can point to further advantages. It allows, for instance, of a more symmetrical and smoothly surfaced combustion head in which the flow and turbulence of the gases can be more closely controlled. It avoids "hot-spots" which result in premature firing of the gases and the "pinking" so familiar to the motorist. It is not uncommonly thought that power is imparted to the piston head through a violent explosion (or "detonation" as the engineers call it) of the inflammable gases. This is very far from the effect the engineer seeks. Premature and uneven burning that has the character of an explosion is not nearly so effective as a relatively slow, even burning that produces a rapid but smooth expansion of the gases in the combustion head. Smoothness of combustion is a prime characteristic of the sleeve-valve engine. There are other technical advantages of the successfully applied single sleeve. A larger and better shaped valve port is possible; as the sleeve moves in the same direction as the piston, but at a slower speed, there is actually less rubbing than if the piston were moving against the stationary cylinder wall, and, contrary to expectation, lubrication is improved by the "wiping" motion of the oscillating and rotating sleeve. In spite of the fact that the sleeve principle allows higher compression ratios to be used, the actual cylinder and exhaust temperatures are lower when compared with poppet-valve engines of similar power output.

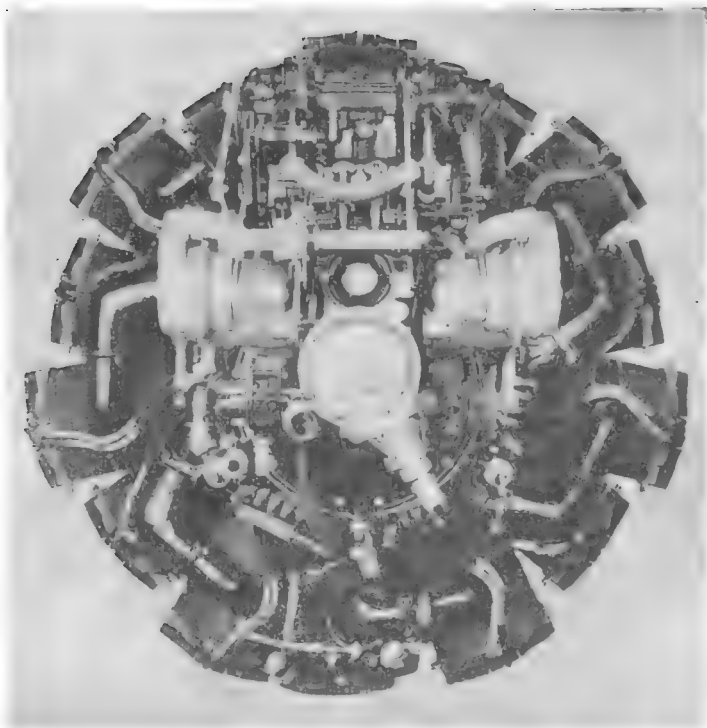
Finally, the sleeve-valve engine, because of the superior

design of its combustion head, has a low fuel consumption. This is an extremely important factor in civil transport, where every pound saved in fuel load is a pound gained in the payload.

At this point one is tempted to say, "If the sleeve valve has all these technical advantages, and I must take the engineer's word for it, why wasn't it developed before? After all, the principle was discovered over thirty years ago". The answer is that practical difficulties often hold up the full realization of the designer's scheme. It must be remembered that the advantages set out above are the advantages of a practical sleeve-valve mechanism that has been proved over and over again in the research unit, on the test bench, and in the air. Before it was incorporated in the "Hercules" engine, for instance, it had been the subject of the day-in and day-out work of one of the finest research and development teams in Great Britain—a British writer might be forgiven for thinking, in the world—for eight years. It needed courage to launch out on such a research programme, a great organization to sustain it, unwearied patience and perseverance to carry it through in the face of difficulties and discouragement.

Some of the more obvious difficulties, as might be expected, centred around the right choice of material for the sleeve. It was found, for instance, that sleeves of nickel cast-iron were unable to withstand the force of the explosion when they masked the ports on the combustion stroke. Cracks and even punctures occurred. This trouble was obviated by using a semi-steel sleeve working in a steel cylinder barrel. But then heating troubles arose to harass the designer.

Finally, sleeves were made from forgings of austenitic nickel-chrome-tungsten steel. One sleeve was used in the normal, relatively soft condition, and the other, for comparison, was "nitrided"—a process that gave a very hard surface. Other detail improvements were made in design, and in the choice of alloys for the cylinder barrel and head. The unhardened sleeve proved unsatisfactory, and the nitrided sleeve was chosen. At this stage the designer throws a problem into the lap of the production engineer. It is an example of that co-operation of



The complete engine, showing the beautiful symmetry of its design. It weighs three-quarters of a ton, is some 52 inches in diameter, and its 14 cylinders give a maximum power output in excess of 1,650 h.p. That is the Bristol "Hercules"—the engine that has been the power behind the wings of all the heavy bombers used by the R.A.F. in the war.

the man in the factory with the man at the designer's drawing-board that is a characteristic feature of British engineering. The designer insisted on the hard, nitrided sleeve, with a wall thickness of something over one-tenth of an inch, accurately machined to a tolerance of twelve ten-thousandths of an inch on the bore and outside diameter; these dimensions had to be accurate through the full 13-inch working length of the sleeve

and over a surface area of something like 220 square inches in each case. Moreover, the surface finish, tested by a special averaging instrument known as a profilometer, is required to give a smoothness standard of a few millionths of an inch. This accuracy over the whole length of the sleeve and fine surface finish are critical factors. Upon the skill with which these machining problems are solved on the production line the successful application of the sleeve-valve principle can be said to depend. Bristol production engineers got to work. They developed a series of special purpose machines to carry out the necessary grinding operations; at the same time great improvements were made in honing and lapping techniques. And they were able to produce a sleeve, under production conditions, that satisfied in every requirement the very exacting demands of the designer. Moreover, the technique evolved was proof against the severe demands of war-time production—when aero-engines had to be built in numbers hitherto thought impossible.

The sleeve-valve mechanism, therefore, as it is applied to the aero-engine, is not the result of a designer's inspiration. It is the result of many years of work by a team of research specialists whose knowledge goes right back to the very foundation of aero-engine building as a precision industry. And its successful application to the high-duty aero-engine has only been made possible by the development of new production processes in the foundry and the machine shop. Developments in the technology of the aero-engine industry can rarely be explained in the colourful, dramatic terms that so easily catch the imagination. Indeed, any attempts to present a highly coloured narrative would falsify the whole picture. There is drama to be sure, but it is the slow unfolding drama of the cool, detached, scientific approach to a problem, the drama of pertinacity in the face of failure, of patient experiment and tireless research. That is the way—the hard way, and the slow way—Bristol technicians solved the problem of the sleeve valve in its application to the air-cooled radial aero-engine.



"STIRLING" BOMBERS—DAILY INSPECTION

Charles Cundall, A.R.A.

Precision Engineering...

how the impeller unit of a "Hercules" supercharger is dynamically balanced

A "HERCULES" ENGINE weighs three-quarters of a ton. It contains some 7,000 separate parts, only about 1,000 of which are different. Some parts are made to a tolerance of .0002 inch. In other words, the engineer must produce a component that does not vary above or below the specified dimensions by two ten-thousandths of an inch—much less than the thickness of a cigarette paper. A normal drawing tolerance for precision fits throughout the engine is five ten-thousandths of an inch. Other parts—the sleeve, for instance—must have a satin-like smoothness of surface. Many components need scores of machining operations. Most machining operations are carried out on the crankcase, which is subjected to something like one hundred and fifty. Each of the separate parts is given a serial number to correspond with the 1,082 separate drawings that are necessary for the latest production engine. Each one of the millions of parts made yearly is engraved with its appropriate number so that accurate, tested spare parts can be ordered from stock without delay or error. It is no figure of speech to say that a production engine is built with the accuracy of a watch; it is no exaggeration to say that a modern aero-engine as exemplified in the "Hercules"—is the finest achievement in precision engineering applied to a mechanism that is put into quantity production.

As an illustration of the care and precision with which many components in a "Hercules" are built and tested, it is of interest to describe how the impeller unit of the supercharger is dynamically balanced. The impeller is really a many-bladed fan that draws air and fuel at a tremendous rate into the induction system, and builds up pressure to force the charge

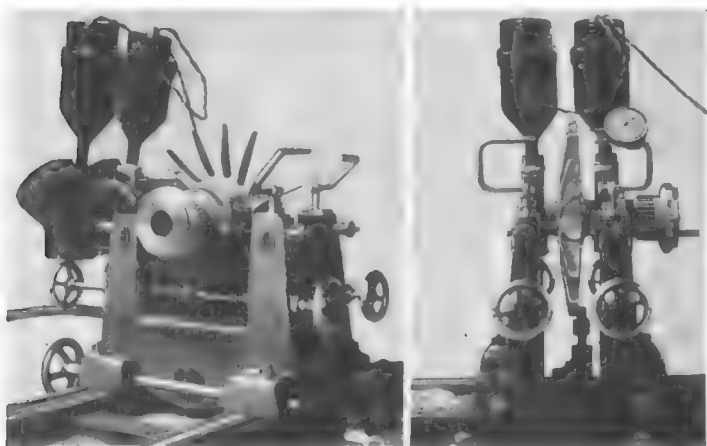
into the combustion head. The impeller must be so accurately balanced that, when it is revolving freely on its bearings, a heavy breath is sufficient to set it rotating. It must be so finely balanced because it revolves at immense speeds when the engine is at full throttle, reaching nearly 30,000 revolutions a minute. At this speed the tips of the blades are travelling as fast as a rifle bullet. At these tremendous speeds, if it were the slightest degree out of balance, a destructive load would be placed on the bearings.

The balancing operation is carried out on a special balancing machine insulated on a massive, vibration-free foundation. In the Bristol factory, a number of these machines are grouped together in a separate room, for every single impeller must be dynamically balanced. The machine measures both "cross oscillation" and "parallel oscillation" while the impeller is running at maximum revolutions and as it gradually slows down through the resonance period of the machine. Oscillations are detected by the behaviour of beams of light in two optical indicating instruments. The impeller, when mounted on the machine, is set in motion by a blast of compressed air. Compressed air is used to avoid the vibration that would be inseparable from any type of mechanical drive. The amplitude of any oscillation reached its maximum during the resonance period of the balancer, and it is shown by the beams of light in the optical instrument travelling out of phase with each other. "Cross oscillation" may be caused by slight inequalities in the thickness of the web of the impeller. By fastening small pieces of plasticine to the web faces in succession this condition is adjusted. The plasticine is then removed and carefully weighed on a sensitive balance, after which a corresponding weight of metal is removed from the diametrically opposite side of the impeller by grinding and polishing. The "parallel oscillation" condition of the impeller is next adjusted similarly, but even more finely, by placing plasticine on the tips of the impeller blades.

The out-of-balance effect permitted, as shown on the scale of the optical instrument, is equivalent to an eccentricity of no more than fifteen hundred-thousandths of an inch. The final

weight of plasticine used in this correction is once more accurately measured, and a corresponding weight removed from the heavy blade or blades by filing and polishing. The metal removed is carefully collected in trays, and frequently weighed until it equals in weight the amount of plasticine used to obtain exact balancing as shown on the optical reading. The required finish of the blade is restored by careful hand polishing, a gauge being used to ensure that the correct profile is maintained.

Finally, the impeller assembly is again placed in the balancing machine and checked by an inspector for alignment of blades, dynamic balance, and correct section, thickness and width of each individual blade. The parts are then separated, identified by engraved markings, and sent through for fitting in the particular supercharger to which they have been allotted.



Two views of the impeller unit of a supercharger mounted in a dynamic balancing machine. The optical measuring instruments, attached to the top of the machine, embody a system of mirrors reflecting beams of light or graduated scales, so that the amplitude of the oscillations, greatly magnified, may readily be observed and recorded.

It must be remembered that the impeller is one component of just one unit—the supercharger—which takes its place among many other units in the completed engine. Other components are finished and tested with equal patience. Nothing can be left to chance. An aero-engine under full load is one of the most heavily stressed pieces of mechanism in the world. Only the rigid application of an inspecting and testing technique, developed over many years, makes it possible to build engines in thousands on the production line, each one of which equals in performance and reliability its hand-built experimental prototype.

Perhaps it is not surprising that British engineers should show a special capacity for the kind of precision engineering that is represented in the quantity production of aero-engines. It is work that calls, at every stage, for the highest attainable standards in engineering practice—with regard to design, materials, methods, workshop processes, inspection and testing. Is it not reasonable to suggest that a tradition of engineering skill and exactitude in workmanship reaching back to the great master mechanics and toolmakers of the nineteenth century in Britain is not without its influence on the men who design and build aero-engines in Britain to-day?

The secret of modern aero-engine efficiency...research, experiment, development work, quality control

THE ACCUMULATED EXPERIENCE of scientists, their latest testing and measuring techniques, and all the instruments known to a modern, completely equipped physical laboratory, are necessary to the production of a precision-built aero-engine. Reference has been made to the fact that an aero-engine is possibly the most heavily stressed mechanism in the world. Yet, because of its special function, it is far and away the lightest unit, in ratio to horse-power produced, that mechanical science has yet evolved. Twenty years ago, designers hardly dared to hope that an engine would be built to yield one horse-power for every pound of its weight. Yet such a power-to-weight ratio is normal among high-efficiency aero-engines to-day.

The designers' drive for improved performance has stimulated the most intense research into the characteristics and performance of metals, the development of entirely new alloys, and the perfecting of research, experimental and quality control techniques that were quite unknown to precision engineering as little as ten years ago.

Routine fatigue testing of materials in the Bristol aero-engine department is carried to what may seem fantastic lengths. Does it need 97,983 vibrations to crack a component being subjected to stresses of 50 tons per square inch at 2,000 vibrations a minute at a temperature of 792 degrees Centigrade? That is a fact these zealous metallurgists think worth noting about a particular piece of metal. After being subjected to a load of 23 tons per square inch for 1,000 hours—or about six weeks—will a component show an elongation of the order of several hundred-thousandth parts of an inch? These exacting men have a machine that is capable of recording the

extent of such minute changes in the length of a bar of steel, to one hundred-thousandth of an inch, at any minute of the day during which the test is taking place. The mechanical testing laboratory at Bristol, undoubtedly one of the best-equipped laboratories of its type in the country, is used as a torture chamber for the engineers' finest handiwork. The modern inquisitors who preside over it take delight in devising the most fiendish ordeals for metals. They heat, stretch, twist, hammer, bend, crack, fracture and break in their efforts to wring from a new alloy the innermost secrets of its strength. The slow death of a component is coolly observed and meticulously charted, measured, tabulated. Give these ruthless men a beautifully machined connecting rod—a part that will stand up to terrific stresses for thousands of flying hours—and they will put it in a machine which, by alternately stretching and compressing it with a load of 10 tons, can break it in two hours.

It would be impossible, in a book of this size, to describe the hundreds of ways in which the research workers of the Bristol organization keep a stream of facts flowing steadily to the designers. Equally impossible to do more than touch the fringe of the measuring and testing techniques that are applied at every stage of research, development and experimental work, and throughout the factory to control the quality and workmanship of components on the production line.

Here, however, are a few highlights that give some idea of the resources, apparatus and the number of scientifically trained research workers that are necessary in an organization that sets out to design and build a modern aero-engine.

The mechanical testing laboratory at Bristol contains a battery of combined bending and torsion fatigue testing machines that are probably the only ones of their kind in the country. Developed by Bristol research workers from an original National Physical Laboratory design, this machine enables a stress consisting of pure bending or pure torsion, or any desired combination of the two, to be imposed on a component at temperatures up to 800 degrees Centigrade. Heat is applied by an electric furnace which surrounds the test piece, and temperature can be controlled to an accuracy

of $2\frac{1}{2}$ degrees Centigrade over the whole thermal range. This machine imposes severe stresses up to plus or minus 50 tons per square inch at 2,000 vibrations (or "stress cycles" as they are called) per minute. In compiling a fatigue curve for a metal, scores of test pieces may be used. For steel, for instance, 40 or 50 pieces taking up to 17 days each may be tested. These machines run continuously, under electric power, day and night, until a given endurance limit is reached or the test piece cracks, in which case the machine automatically stops and records the number of vibrations (or "cycles") necessary to produce the flaw. The endurance limit set for light alloys is 100 million cycles. This means that a test piece must be able to withstand a bending or twisting strain, or a combination of the two, amounting to 50 tons per square inch applied continuously at the rate of 2,000 stresses a minute for a period of something over a month. The Mechanical Testing Laboratory at Bristol, containing many such machines, is built on massive concrete foundations to absorb the vibrations set up by batteries of the machines working in unison.

Much useful information is obtained by the use of electric strain gauges. An electric strain gauge is really a coil of fine wire, one-thousandth of an inch in diameter, wound on a flat former and contained between layers of resin-impregnated paper. The complete gauge, which is only about five-thousandths of an inch thick, is then cemented firmly to the test piece, component, or any part of the engine. Stresses which produce the most minute change in the dimensions of the metal, stretch or compress the fine gauge coil of wire and so change its resistance. This change in resistance, while an electric current is passing through the coil, can be registered visually on a cathode-ray oscillograph. It appears as a line of light moving swiftly across a dark glass screen. When a stress is being measured, this line runs along the screen as a rhythmic wave, and the extent of its movement from the horizontal is a measure of the stress imposed. By this means, it is possible to measure to an accuracy of 5 per cent. a change of dimension of the order of one ten-thousandth part of an inch. It would not be thought, for example, that a steel bar of half-inch



PRODUCTION OF A VICKERS ARMSTRONG "WELLINGTON" MARK I. A. BOMBER *Harold Bubb*

section and only about two feet in length could be affected by muscular pressure exerted when it is picked up in the hands. But when strain gauges are attached to the bar, even slight pressure exerted in an attempt to bend the bar produces violent agitation of the light on the oscillograph—showing that the minute changes of dimension produced by the bending stress imposed is actually measurable by this sensitive apparatus.

In the testing of components a new technique can now be used that displaces the conventional micrometer and gauge. The component to be inspected is mounted in a machine which projects an image, greatly magnified, on to a translucent detailed drawing of the component. Thus the contours of the part can be compared exactly with the designer's blueprint from which it has been made.

Inspection of castings and forgings is often carried out with the help of an electronic flaw detector. With this apparatus the inspector can actually peer beneath the surface of the metal and detect an inner flaw that could not possibly be revealed by surface inspection. Such hidden flaws can also be exposed by the use of X-ray photographs or through a method of observing the disturbance of the magnetic field around the component when an electric current is passed through it.

In the Standards Room, in a temperature-controlled and air-conditioned atmosphere, master gauges used in the factory are frequently checked. The instruments employed are capable of measuring to one-millionth of an inch. The heat of the hand, for instance, is sufficient to cause expansion in a small piece of metal. This change of dimension, minute though it is, can be recorded by these ultra-sensitive instruments. Readings are taken by observation of the movement of a hair-line of light on an illuminated scale. The scale is seen through an optical instrument that greatly magnifies the images observed.

A new technique, using heat-sensitive paints, has been developed for measuring the temperature changes that take place in an engine under running conditions. Parts of the

engine are painted before assembly; after a running test the engine is stripped down and the changes in colour of the paint carefully compared with samples that have been subjected to measured degrees of heat. Thus a complete picture can be built up of the temperature changes that take place all over the engine. It is not generally known, for instance, that considerable friction heat is generated in an aero-engine, apart from the heat of combustion. This friction heat alone, in an engine running at full power, amounts to the output of some hundreds of ordinary domestic heaters. The designers, with such knowledge in front of them, can make more accurate calculations of the cooling requirements of a particular design.

Refinements such as those described here in measuring, testing, inspection and research techniques have been automatically adopted at Bristol as they were developed. In addition, Bristol engineers have exercised considerable ingenuity in devising their own methods for the compiling of research data, or for the improving of quality control over materials and workmanship in production processes. It would be true to say that the full resources of the physical, metallurgical, mechanical, electrical and electronic departments of science are brought into the service of the engineers, at one stage or another, in the designing and building of Bristol aero-engines. And it is reasonably certain that no other organization in the world has better research facilities, both as to scale of equipment and number and experience of scientifically trained personnel, for the solving of the special problems likely to be raised in the future development of the air-cooled internal combustion engine.



A battery of combined bending and torsion fatigue testing machines in part of the mechanical testing laboratory at Bristol. In the foreground a machine is shown in course of erection.



A research worker watches the deflection of the beam on a cathode-ray oscilloscope, brought about by the change in inductance of an electric strain gauge.



Preparing a quarter-scale model of a "Hercules" engine in the design office model room. Models greatly assist the designer in his preliminary work on a new engine.



Testing a connecting rod in a fatigue testing machine. By applying a "push and pull" strain of 10 tons per square inch this machine can break a connecting rod in two hours.



The operator, using this precision measuring machine in the Bristol standards room, can measure lengths up to 40 inches with an accuracy of ten-millionths of an inch. The standards room is air-conditioned and temperature-controlled.



Three creep testing units in the mechanical testing laboratory. By means of mirror extensometers these machines can record an elongation of a specimen to an accuracy of one hundred-thousandth of an inch.



In this fatigue testing machine a bending stress is being applied, one end of the test piece being deflected at 2,000 stress cycles a minute while the other end remains fixed.

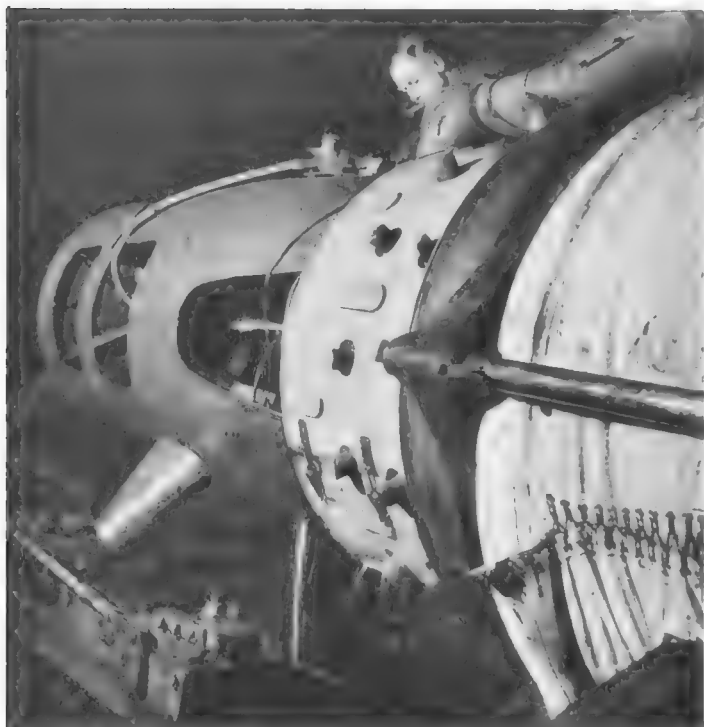
What of the Future . . . gas turbine or piston engine?

QUITE RECENTLY readers of the daily Press in most countries were somewhat startled to learn that aircraft had been flying without propellers. It was, indeed, a revolutionary development. It meant that an entirely new prime mover—the gas turbine—using an entirely new principle of propulsion—the reaction jet—had been successfully adapted for use in an aircraft.

Does this mean that the days of the piston engine are numbered? Are reciprocating internal combustion engines, such as the “Hercules”, already out of date? These questions must be approached with caution. First it must be obvious, from the rapid technological development of the aero-engine industry over the past quarter of a century described here, that there is no engineering problem that is likely to baffle human ingenuity indefinitely. Equally obvious is the fact that a high-duty internal combustion engine with a performance fitting it for use as the power plant of an aircraft needs many years of intensive research and experimental work to bring it to the production stage.

It takes, for instance, in the designing of a piston engine, five to six years before it goes into quantity production. It can be safely predicted, therefore, that there are many practical problems to be solved before the gas turbine can be generally applied to aircraft. This is true of the gas turbine whether it is used to drive a propeller—as it may be—or solely as a jet-propulsion engine.

The fuel consumption of the gas turbine, for instance, is at present some two to three times that of a piston engine of similar power at normal speeds and altitude. On the other hand, the installed weight of a gas turbine is only about half



A view of the engine on the test bench taken from inside the sound-proof test house. One of the test crew is here setting the boost before a test run. Each engine is tested, then stripped down, all components examined, then rebuilt before it has a final test. Nothing is left to chance in the building and testing of the "Hercules".

that of a modern piston engine of equal power. We have seen how vitally important this power-to-weight ratio is in the power plant of the heavier-than-air machine. There can be no doubt, therefore, that great effort will be made to improve fuel consumption of the turbine.

It is interesting to note here that the development of the gas turbine—long known to engineers as a desirable type of prime

mover—has been held up by limitations imposed by the characteristics of the metals available for making the turbine blades. Just such another limitation imposed on the designer by the materials available as we saw operating in the case of the sleeve valve. It is only a few years ago—and as a result of the intensive development of the turbo-supercharger—that special heat-resistant blades have been made capable of withstanding the enormous heat of the gases used in the gas turbine.

At the moment it seems likely that the piston engine will hold the field for the medium speed medium altitude class for some years and will have advantages over the turbine in the lower horse-power categories.

With these considerations in mind, Bristol engineers, while not neglecting the gas turbine, are concentrating on the designing of piston engines giving a power output far in excess of the present maximum range. The "Centaurus", for instance, an 18-cylinder two-row air-cooled radial engine, is yielding well over 2,500 h.p. Future development should see the production of piston engines of the 4,000 h.p. class.

However, there is no escaping the fact that the efficiency factor of a piston engine is only about 30 per cent. Much of the power generated by the piston engine cannot, by the very nature of its design, be utilized; it is dissipated through the exhaust pipes. It has been found possible, and this is a fact not generally known, to obtain a small "reaction" or jet-propulsion effect from these exhaust gases. Thus the high speeds of British fighter aircraft are due in part to careful planning of exhaust systems to make use of this jet-propulsion effect. But the amount of energy that can usefully be converted in this way is severely limited.

Then again, at high speeds and at high altitudes the propulsive efficiency of the propeller falls away rapidly as compared with the gas turbine and jet unit, becoming not more than half that of the latter.

It seems certain, therefore, that the gas turbine—particularly in the high horse-power categories—is destined to replace the piston engine as a prime mover for many types of



**THE SHORT "SHETLAND" FLYING-BOAT
WITH FOUR BRISTOL "CENTAURUS" ENGINES**

aircraft. But few engineers would be prepared to conjecture when that time will come.

In the engineering field many revolutionary inventions have developed side by side with the machines they were supposed to replace. The very production of a new prime mover seems to act as a stimulant to the engineers working on the established system. There was a time, at the close of the last century, when engineers predicted that the newly invented steam turbine was bound to oust the steam reciprocating engine. Yet to-day the reciprocating engine still powers 90 per cent. of the world's locomotives and 60 per cent. of the world's steam-driven ships. To draw upon an example from the aero industry, we have seen that the sleeve valve has many theoretical advantages over the poppet valve. As it has been developed for the "Hercules" and "Centaurus" engines Bristol engineers might fairly maintain that, for many purposes, it now shows certain practical advantages. But it could hardly be claimed that the future of the piston engine necessarily depends upon universal application of the sleeve principle.

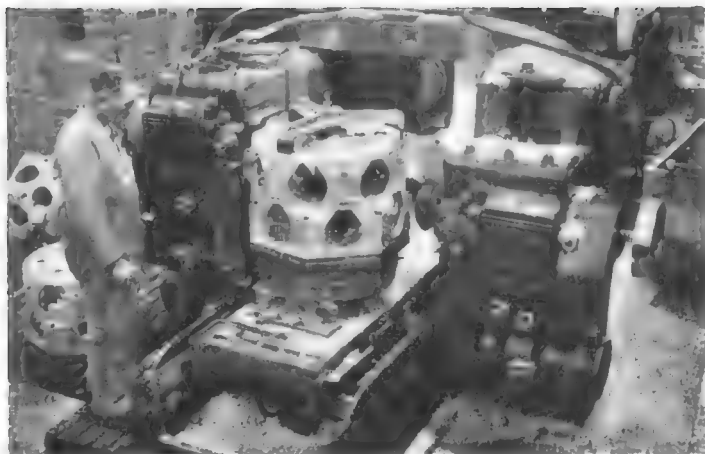
So we can say that the piston engine may still look forward to a long and useful life in air transport side by side with the development of the gas turbine. One thing can be said with certainty. The Bristol designers who have so powerfully influenced the development of the air-cooled radial engine over the last quarter of a century will not be found wanting, either in vision or experience, when the gas turbine is at the stage where it is likely to replace the piston engine as the prime mover for aircraft. And through their practical day-to-day research and development work on the application of the gas turbine to aircraft, there is no doubt that the Bristol organization will continue to make in the future, as it has in the past, many useful contributions to aeronautical science.

The building of a "Hercules" Aero-engine

The production of a modern aero-engine in the great numbers achieved in the war years in Great Britain would not have been thought possible a few years ago. For every production engine must be precision built. Bristol tool makers, production engineers and inspectors have had to solve many difficult problems, develop a number of special purpose machine tools and evolve new inspection and testing techniques, in the making of "Hercules" engines on a flow production basis. They have been helped by the fact that British engineers seem to show a special capacity for this kind of precision engineering. There can be no doubt that in every Bristol "Hercules" engine British workmanship is found of a quality that has become traditionally associated with the products of Britain's engineering industry.



A view of part of the Bristol power plant design office, where designs are prepared for the engine considered as a complete power-producing unit ready for installation in an aircraft.



Milling the cylinder faces of the crankcase, which comprises three light alloy forgings bolted together to form one unit. This Duplex mill machines upper and lower faces of the crankcase at the same time.



Drilling bolt holes in the crankcase. The bolt holes are drilled and counter-sunk in one operation. Many of the most modern machine tools in the world are to be found in the Bristol factory.



Profiling exhaust port facings on the cylinder barrel. Facings are profiled with form cutters, hydraulically controlled from a master form plate. In the foreground are piles of the massive, semi-finished cylinder barrels.



A modern multi-drill used for drilling holes in the cylinder barrel. Motorists will be interested in the massive size, yet relative lightness, of a "Hercules" cylinder barrel as proved by the ease with which the girl operator lifts it.



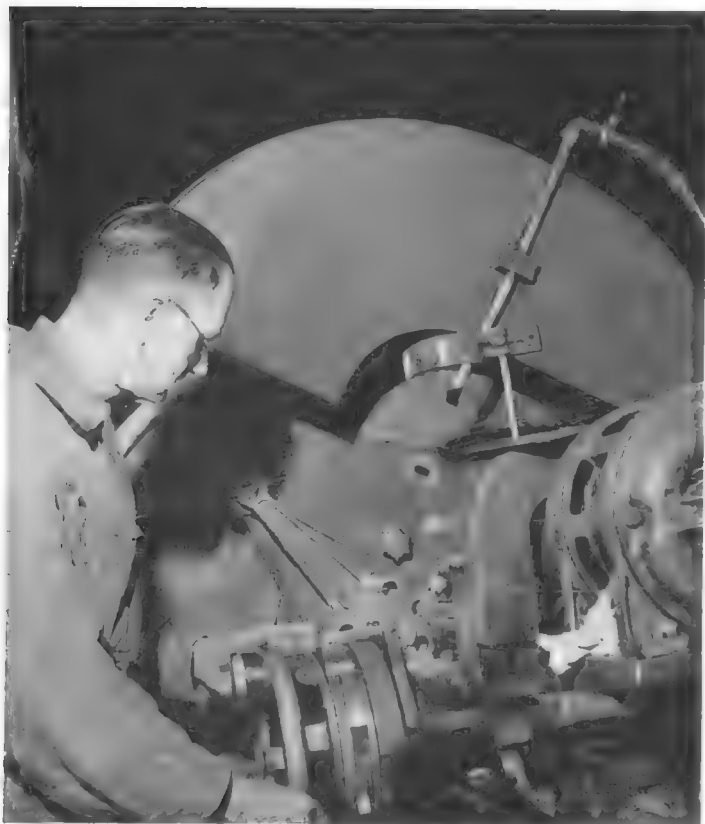
Fourteen tools, mounted in a special tool holder, are used in this machine to complete turning operations on the cylinder head. A modern aero-engine plant of the size of Bristol must be equipped with machine tools worth millions of pounds.



A view of some of the massive, electrically driven machine tools used in the making of "Hercules" engines. These are machines for the drilling and tapping of cylinder stud holes in the crankcase.



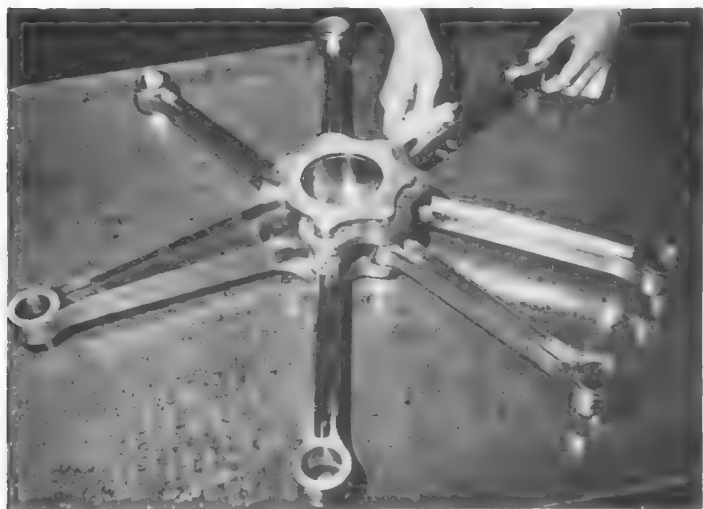
A critical operation. Centreless grinding of the sleeve, which must be accurate to two ten-thousandths of an inch on the bore. Ovality must not exceed one-thousandth of an inch over the whole 14-inch length of the complete sleeve.



Grinding wrist pin holes in the master connecting rod. The use of a master connecting rod for each bank of seven cylinders in the "Hercules" engine is an adaptation of a scheme first used with great success on the "Jupiter".



The development of rigorous inspecting and testing techniques has been a vital factor in the making of a precision-built engine in great numbers. Here the master connecting rod is being tested with a sensitive caliper gauge.



A master connecting rod of the "Hercules" with the other six connecting rods of a bank in position as they would function in the assembled engine. Two sets of seven connecting rods, assembled as this, are used.



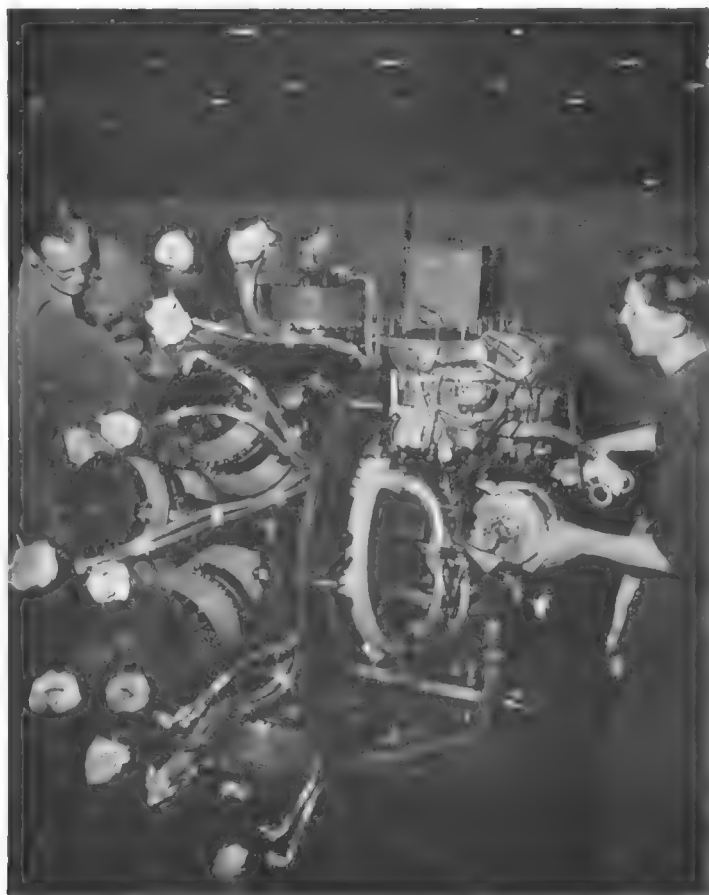
Inspection of the airscrew shaft in a crack detector. The component is cleaned, then dipped in detecting ink. A low voltage electric current is then passed through, and flaws detected by the adhesion of minute particles of ink to the edge of the crack.



A line of test houses. Each building contains two test beds. Each engine is run by electricity for five hours and then submitted to a one-hour endurance test under its own power. Test houses are sound-proofed to deaden noise.



Looking through the inspection window at an engine on the test bench. Artificial conditions of altitude and airspeed are created. Power output, oil and petrol consumption, temperatures, blower power and other particulars are logged with the aid of instruments on the instrument panel in foreground.



Setting the ignition timing of an engine during assembly. Once the engine is assembled there is no need for adjustment of valves, since each sleeve is positively operated through a train of gears. This is one of the practical advantages of the sleeve-valve over the poppet-valve system.

“Aeronautical engineering is ordinary engineering made more difficult.”

DR. R. V. SOUTHWELL
*in the James Forrest Lecture to the
Institution of Civil Engineers.*

